STUDIES IN EVAPORATION AND TRANSPIRATION[1]

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(WITH FIVE FIGURES)

As the result of studies extending over several years, considerable experimental data have been accumulated concerning the transpiration of alfalfa and other plants under various accurately measured conditions of temperature, relative humidity, and wind movement. It was found, however, that the interpretation of these results was hopeless unless something more was known about the quantitative influence of these factors upon purely physical evaporation than was available to the writer. Thus it was impossible to say whether a given result was simply the product of the physical factors then obtaining, or to what extent it was modified by the physiological reactions of the plant itself. One should be able to calculate from rational formulae the behavior of a physical evaporating surface for the given conditions. Any departure from this result could then be attributed to the response of the living organism.

It may be assumed that the general type of such a formula will remain the same for all situations, but that the constants will vary with all of the varying conditions of environment, temperature, wind movement, relative humidity, and size and nature of the evaporating surface. The purely physical experiments here reported were designed, first to work out the generalized type of the formula, and then to obtain the constants for certain special cases of environment and other factors. Environment is used here in a restricted sense, meaning only the size and nature of the space within which the evaporating surface is inclosed. In the work reported this was one liter of space included within a glass cylinder closed by two large rubber stoppers at either end. When

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[1] These experiments were conducted at the University of Arizona Agricultural Experiment Station during the writer's connection with that institution, which extended over the years 1909–1918. They were, for the most part, conducted during the latter part of this period.

a surface is evaporating in the open, the environment is unbounded or indefinite. It differs from the closed environment, not in type, but in degree, since where there is any wind movement, after a greater or less length of time, the evaporating surface will come into equilibrium with it, and thereafter give off water at a uniform rate. The larger the environment and the slower the wind movement, the longer will be the time required to reach this equilibrium. With an unbounded environment and no wind movement, theoretically it would never be reached, but for all practical purposes a small evaporating surface exposed in the open in still air soon reaches a uniform rate of evaporation, which will remain constant so long as the temperature and dewpoint of the air remain the same. The influence of the size of the environment, therefore, is capable of mathematical expression, and may enter as a factor in a rational evaporation formula. When the size of the environment always remains the same, as in all the experiments conducted by the writer, this factor may be left out of the formulae as a variable, that is, its value may be included in one of the other constants found. When the size or nature of the environment varies in any way, it must be calculated as a separate constant, or else the other constants (which had included it) must be recalculated for each new environmental condition. It is this consideration which has made it impossible to write, for any given type of surface, an evaporation formula which would apply to all situations, even though all be in the open. The reason for this is that every environment is more or less restricted by buildings, trees, banks, hills, or mountains, so that no two are exactly alike. It would be impossible to write a formula which would account for all of these variations. So long, however, as we confine ourselves to a given environment and a given type of evaporating surface, we can easily account for variations in amount of surface, temperature, wind movement, and dewpoint of the air.

In the physical experiments undertaken, the evaporating surface used was a porous cup atmometer. A constant stream of air was drawn through the cylinder (over the atmometer) by a rotary air pump driven by a small motor. The air was measured by a water gasometer which was accurate to 1/1000 of a cubic foot.

The dewpoint of the incoming and outgoing air was determined by the interjection of the base of a polished nickel test-tube into the air stream. Ether within the tube was cooled by blowing a current of air into it with an atomizer bulb. When the ether and the tube were cooled to the dewpoint of the air stream, the formation of a film of dew on the outside of the test-tube could be observed. A delicate thermometer having its bulb immersed in the ether was then quickly read to 0.1 of a degree, which appeared to be sufficiently accurate for all practical purposes. In the following discussion only the dewpoints of the incoming and outgoing air are given. Anyone desiring to know the absolute evaporation can quickly calculate it from these data; but for the purposes of this discussion this is not necessary. Let y = rise in dewpoint of outgoing air over that of the incoming air; t = temperature of air; t_1 = dewpoint of incoming air; z = a constant, the value of which will depend upon the rate of air movement (w) and the size and nature of the evaporating surface. The value of y may then be expressed by the formula $y=z(t-t_1)$. The agreement of this formula with the experimental results is shown in fig. 1. This gives the results of an experiment in which the temperature was artificially raised and controlled, giving a range from 16.4 to 25.2° C. Since the dewpoint of the air used remained constant at 3.0°, there was a range in the value of $t-t_1$ of 8.8°. The lines ot and ot_1 give the value of t and t_1 respectively. The line oy gives the calculated value of y when $z=53$ per cent. The dots show the agreement of the experimental with the calculated value of y. So long as other factors remain the same, the value of y appears to

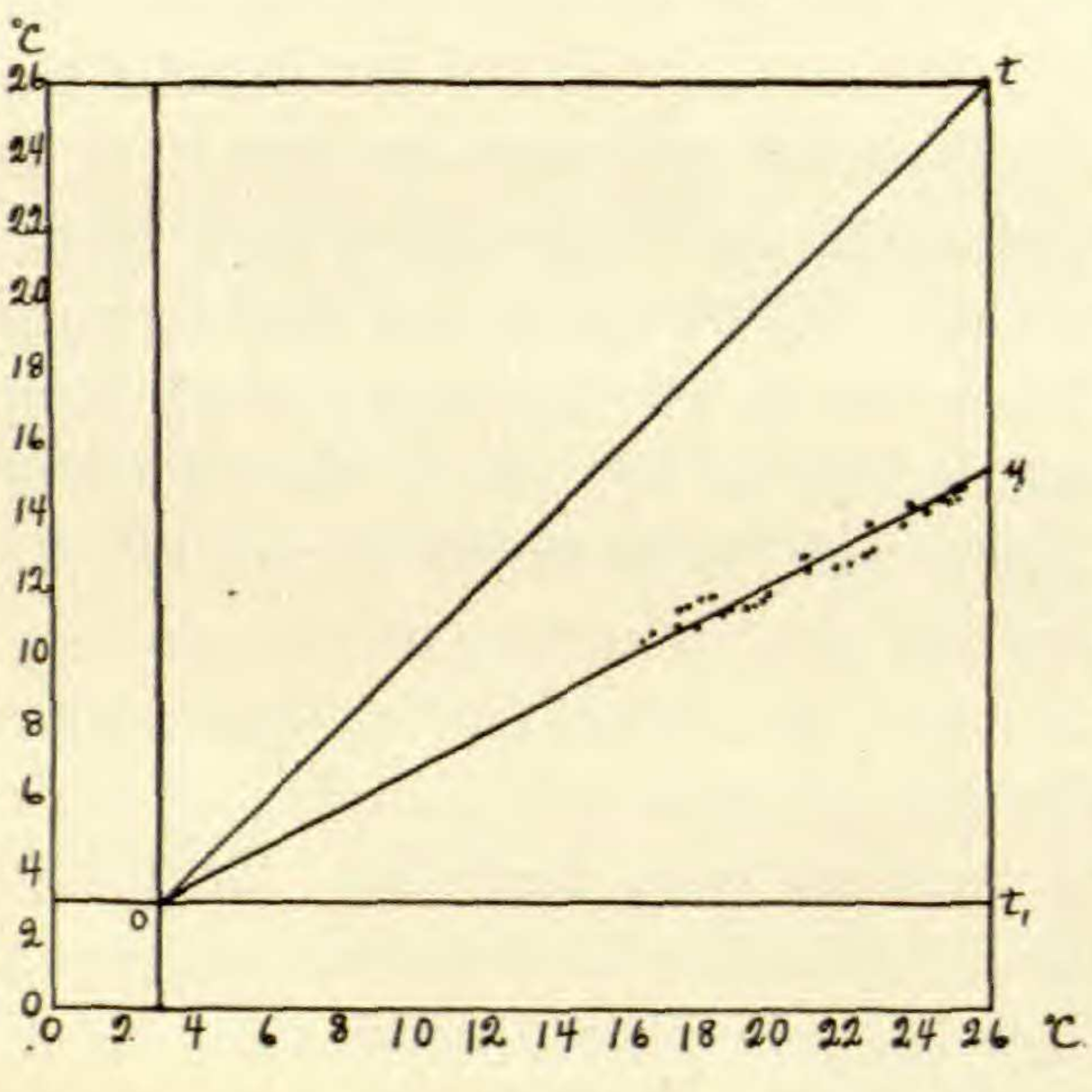

FIG. 1

be a constant linear proportion of the rise of t. A number of other experiments were made which exhibited a similar agreement between the experimental and calculated results. All of these are summarized in fig. 2, in which the ascending line oy represents the calculated value of y, while the dots show the experimental results obtained.

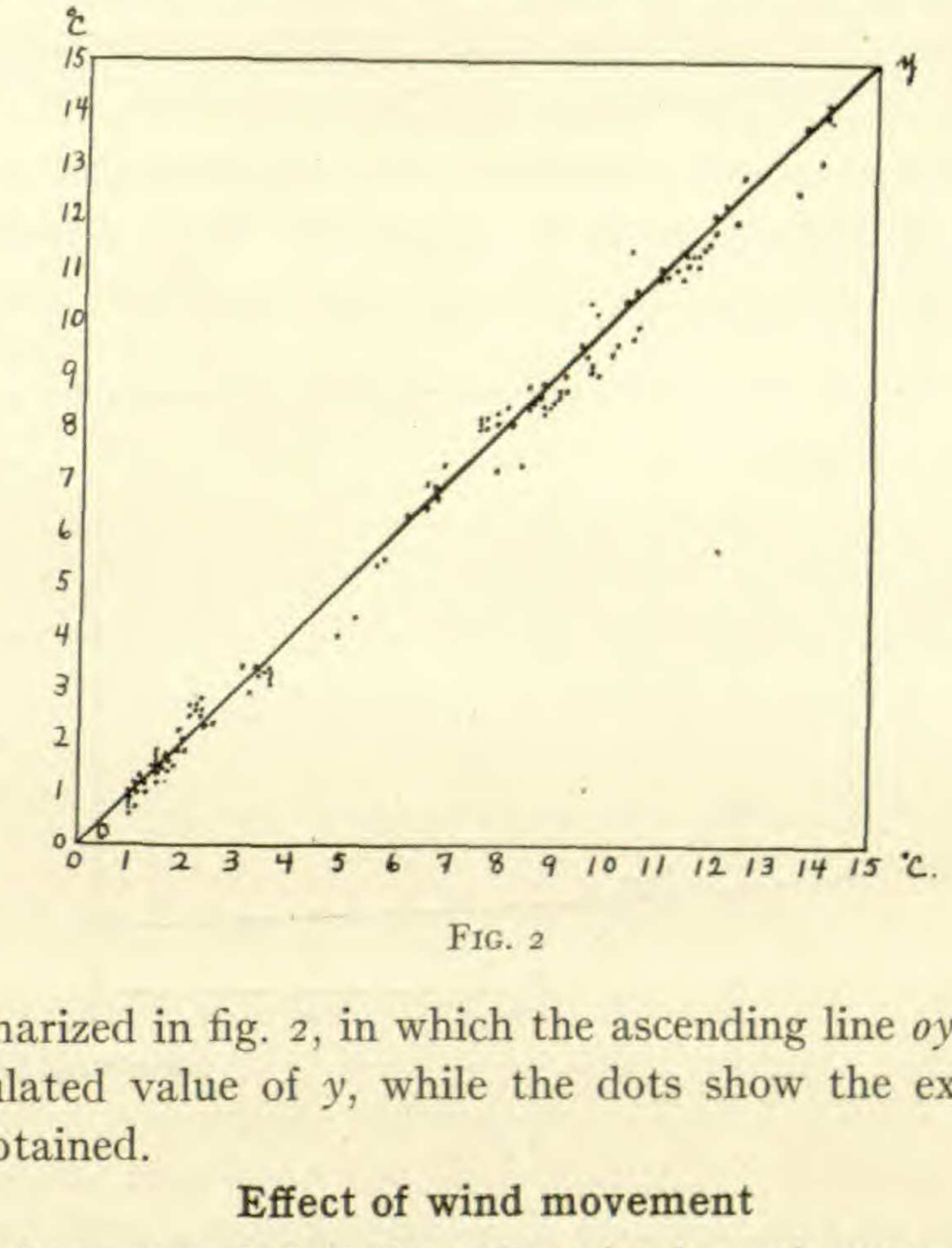

FIG. 2

Effect of wind movement

It has been stated that the value of z depends upon the rate of air movement (w) and the extent and nature of the evaporating surface. When the latter remains unchanged and only wind movement is varied, z takes the form of $z=\frac{1}{1+c(w)^n}$, in which c and n are constants. The formula then becomes $y=\frac{t-t_1}{1+c(w)^n}$. In using this formula it is convenient to plot the results as is shown in fig. 3; ot is the temperature of the air, and o_1t_1 is its dewpoint; both of which are here constant at 21° and $-1.8°$ respectively. The rate of wind movement may be plotted along o_1t_1, from which the found values of y may be plotted as ordinates. The curved line oy joining these ordinates then gives the value of y, which is seen to decrease as the rate of wind movement is increased. Now let a line bisecting the right angle at o cut oy at c. The ordinate from o_1t_1 passing through c will give a value of w which may very conveniently be used as the unit. Now since $1^n=1$, the value of y at this point becomes $y=\frac{t-t_1}{1+c}$; hence $c=\frac{t-t_1}{y}-1$. By substituting this value of c into the formula with other experimental values of y and w, the value of n can be obtained readily. A more general method of finding the value of n is by the elimination of c, as follows: Going back to the original formula and solving for cw^n, we find that: $cw^n=\frac{t-t_1}{y}-1=p$; likewise $cw_1{}^n=\frac{t-t_1}{y_1}-1=p_1$; dividing $\left(\frac{w}{w_1}\right)^n=\frac{p}{p_1}$; whence $n=\frac{\log\frac{p}{p_1}}{\log\frac{w}{w_1}}$.

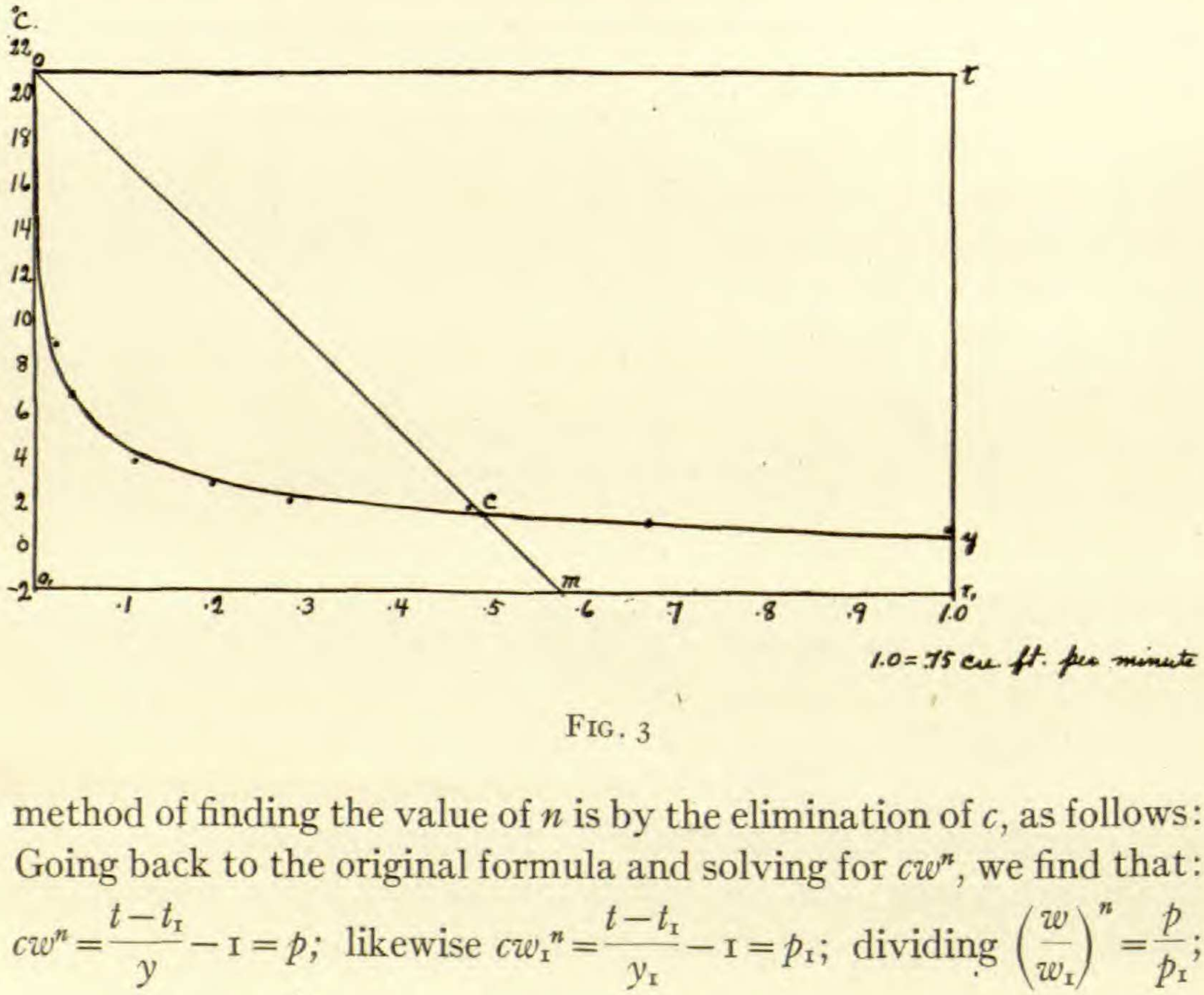

FIG. 3

Knowing the value of n, we can readily find c by the formula $c=\frac{p}{(w)^n}$. The first method for finding the value of c and then of n is quicker and more accurate when as many as four or five experimental points on the curve oy are known, thus enabling one to locate the point *c* with reasonable accuracy. When only two or three points are known, however, the second method should be used. By the first method, when 0.485 cu. ft. of air per minute was the unit of wind movement, the values of *c* and *n* were found to be 5.706 and 0.5 respectively. With these data the complete theoretical curve *oy* may be calculated and plotted, and the provisional curve used in finding the point *c* corrected and extended.

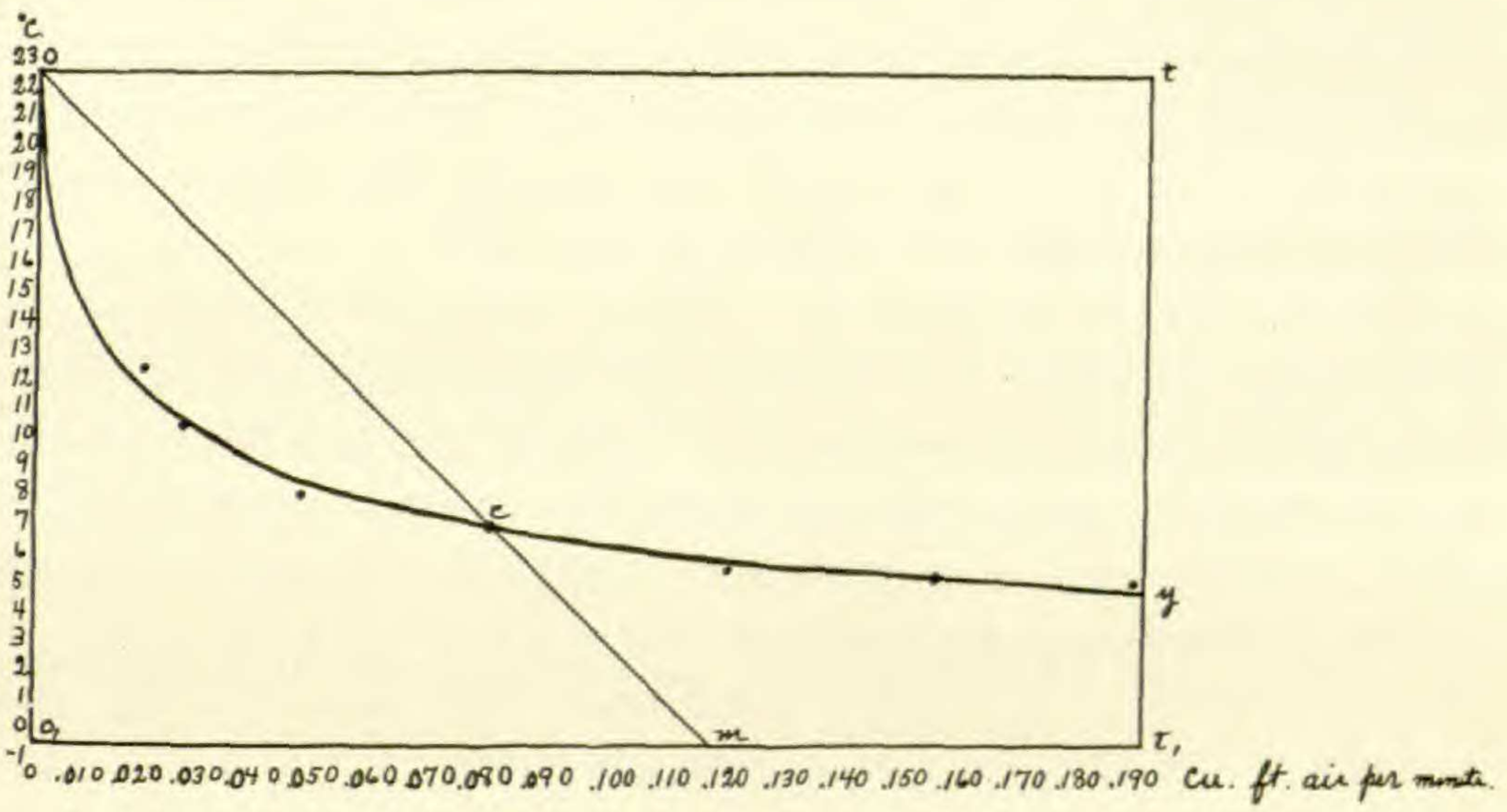

FIG. 4

In fig. 3 the complete curve given is the calculated theoretical curve, and the dots show the close adaptation of the experimental data to it. The agreement appears almost strikingly complete.

Fig. 4 gives an experiment of a similar nature in which $n = 0.58$ and $c = 2$. In this figure the wind movement is drawn on a larger scale than in fig. 3. As will be seen later, the factor *c* includes both the corrections for the area and the nature of the evaporating surface, and to adjust the temperature and wind movement factors to each other. The correspondence of the experimental results with the theoretical curve is again quite close, as is shown by the dots.

It now remains to determine the influence of changes in the area of the evaporating surface, assuming that its character remains constant. Changes in the evaporating area will affect both *c* and *n*. As the area at which *c* is determined rises, the value of c is diminished; and when the evaporating surface practically fills its environment, c approaches zero. On the other hand, as the area at which c is determined is made smaller, the value of c indefinitely increases.

As the evaporating area increases, the value of n increases, until when the evaporating area practically fills its environment, the value of $n=1$ (that is, the air passing off will be saturated and the evaporation will be in direct linear proportion to the rate of wind movement). Conversely, when the size of evaporating area is diminished, the value of n decreases, until it reaches the vanishing point, when the evaporating area becomes indefinitely small. When n becomes zero, the value of w^n will equal 1, regardless of the numerical value of w, since any number raised to the zero power equals one. In other words, when the evaporating area is indefinitely small, it cannot measurably increase the humidity of the surrounding air; hence changes in wind movement would have no effect upon the rate of evaporation. Instead of c we may therefore write $\frac{c}{a}$, and for n write $\frac{a}{k+a}$, in which a is any area expressed in terms of the area used when c was determined, and k is a constant. The formula then becomes $y=\dfrac{t-t_1}{1+\dfrac{c(w)^{\frac{a}{k+a}}}{a}}$. Again, if the wind movement used when c and k were determined be made unity, and other wind movements be expressed in terms of it, since 1 raised to any power is 1, the formula for that wind movement becomes $y=\dfrac{t-t_1}{1+\dfrac{c}{a}}$, from which the value of c can readily be calculated from any experimental value of y. This statement of the formula can also be used in experiments in which the wind movement is not varied, and may hence be considered as unity. The details of such an experiment are given in table I, where $c=0.984$, $w=1$, $a=1$, and $a_1=1.654$. Since $w=1$ throughout, the determination of k was unnecessary.

Table II gives another experiment of a similar nature, in which the wind movement was 91.43 liters of air per hour throughout, which

TABLE I

EVAPORATION EXPERIMENT WITH ATMOMETER

Temperature outside	Dewpoint outside	Dewpoint of escaping air	Evaporating surface	Found y	Calculated y	Difference
27.0.....	0	13.8	45.8 sq. cm. = 1	13.8	13.5	−0.3
26.0.....	0	13.2	45.8 sq. cm. = 1	13.2	13.0	−0.2
26.0.....	0	12.8	45.8 sq. cm. = 1	12.8	13.0	+0.2
25.9.....	0	12.8	45.8 sq. cm. = 1	12.8	13.0	+0.2
	Average.....		....	13.2	13.1	−0.1
27.0.....	0	16.2	75.47 sq. cm. = 1.645	16.2	16.8	+0.6
26.0.....	0	16.2	75.47 sq. cm. = 1.645	16.2	16.2	0
26.1.....	0	15.8	75.47 sq. cm. = 1.645	15.8	16.2	+0.4
26.1.....	0	16.0	75.47 sq. cm. = 1.645	16.0	16.2	+0.2
	Average.....		....	16.1	16.4	+0.3

is here used as unity. The other constants were as follows: $c = 1.257$, $a = 42.04$ sq. cm., here taken as unity, and $a_1 = 75.47$ sq. cm. $= 1.7954$.

There remains to show the details of an experiment in which both the area and wind movement were varied. Here $a = 52.98$

TABLE II

EVAPORATION EXPERIMENT WITH ATMOMETER

Temperature outside	Dewpoint outside	Dewpoint of escaping air	Evaporating surface	Found y	Calculated y	Difference
21.7.....	1.0	10.6	1	9.6	9.2	....
21.5.....	1.0	10.2	1	9.2	9.1	....
21.2.....	1.0	10.0	1	9.0	8.9	....
21.0.....	1.0	10.4	1	9.4	8.9	....
20.9.....	1.1	10.0	1	8.9	8.8	....
20.8.....	1.1	10.1	1	9.0	8.7	....
20.8.....	1.2	10.2	1	9.0	8.7	....
20.7.....	2.2	11.2	1	9.0	8.2	....
20.7.....	2.3	10.5	1	8.2	8.1	....
20.7.....	2.2	9.8	1	7.6	7.6	....
	Average.....		....	8.9	8.6	−0.3
21.7.....	2.2	13.6	1.7954	11.4	11.5	....
21.6.....	2.3	13.5	1.7954	11.2	11.4	....
21.4.....	2.3	13.6	1.7954	11.3	11.2	....
21.0.....	2.2	12.7	1.7954	10.5	11.0	....
21.0.....	2.2	12.8	1.7954	10.6	11.1	....
	Average.....		....	11.0	11.2	+0.2

sq. cm., taken as the unit of area, $a_1=75.47$ sq. cm. $=1.42$, $k=3.546$, $c=1.076$; $w=91.43$ liters per hour, here used as unity, and $w_1=165.62$ liters per hour $=1.816$.

The calculated and experimental results again agree so closely that the conclusion seems justified that they are within the limits of experimental error.

TABLE III

EVAPORATION EXPERIMENT WITH ATMOMETER

Temperature outside	Dewpoint outside	Dewpoint of escaping air	Evaporating surface	Wind movement	Found y	Calculated y	Difference
25.2......	2.2	13.0	1	1.816	10.8	10.3	....
25.1......	2.2	12.7	1	1.816	10.5	10.3	....
25.0......	2.2	12.4	1	1.816	10.2	10.2	....
24.9......	2.2	12.3	1	1.816	10.1	10.2	....
	Average		....	....	10.4	10.3	−0.1
25.3......	1.0	13.0	1	1	12.0	11.7	....
25.4......	1.0	12.9	1	1	11.9	11.8	....
25.4......	0.9	12.7	1	1	11.8	11.8	....
25.4......	1.1	12.6	1	1	11.5	11.7	....
25.4......	1.0	12.4	1	1	11.4	11.7	....
	Average		....	....	11.7	11.7	0.0
27.0......	1.1	15.2	1.42	1	14.1	14.7	....
26.8......	1.2	15.2	1.42	1	14.0	14.6	....
26.6......	1.2	14.8	1.42	1	13.6	14.5	....
26.4......	1.1	16.0	1.42	1	14.9	14.4	....
26.2......	1.0	15.2	1.42	1	14.2	14.3	....
26.1......	1.0	15.3	1.42	1	14.3	14.3	....
	Average		....	....	14.2	14.4	+0.2
26.0......	1.2	14.2	1.42	1.816	13.1	13.1	....
25.8......	1.3	14.4	1.42	1.816	13.1	12.9	....
25.4......	1.4	13.6	1.42	1.816	12.2	12.6	....
25.3......	1.4	13.8	1.42	1.816	12.4	12.6	....
	Average		....	....	12.7	12.8	+0.1

An examination in detail of the completed formula will show whether it will continue to appear rational when the several variables concerned are carried to their extreme limits. As t increases, y will increase indefinitely. As t decreases, y will decrease and vanish when t falls to t_1, or to absolute zero. As t_1 increases, y decreases and vanishes when t_1 reaches t. As t_1 decreases, y increases until t_1 reaches absolute zero, at which the size of y will depend on t, a, and w only. As a increases, the value of the expression $\frac{c(w)^{\frac{a}{k+a}}}{a}$ decreases, until when a is indefinitely large it vanishes; hence the value of y will equal $t-t_1$, that is, the air will be saturated for the temperature t. At the same time the expression $\frac{a}{k+a}$ will approach 1; that is, as the size of the evaporating area increases in relation to its environment, the more dependent is the rate of evaporation upon the wind movement. On the other hand, if a decreases, the value of the expression $\frac{c(w)^{\frac{a}{k+a}}}{a}$ increases and approaches infinity, at which point y would equal zero. At the same time the expression $\frac{a}{k+a}$ will approach zero. In other words, when the evaporating area decreases, the rate of evaporation depends less and less upon the wind movement. As w increases, the value of y will decrease, and vanish when w reaches infinity. As w decreases, y will increase; and when w becomes zero, the value of y will equal $t-t_1$, that is, the air will become saturated for temperature t. It thus appears that the formula remains rational when any of its variables are projected to their extreme limits. Moreover, it appears to correspond, within allowable limits of experimental error, with the results obtained throughout the range of conditions covered by the work of the writer. This range does not include temperatures either above the boiling point or below the freezing point of water. Disturbing factors which might be introduced at those critical stages in the physical condition of water were not investigated, inasmuch as they would practically never be reached in investigations concerned with the transpiration of living plants.

Fig. 5 gives the results of an experiment made upon a potted alfalfa plant. The temperature was raised artificially by means of an electric current passed through a coil of nicrome wire. This was wrapped around the cylinder into which the branches were inserted from below through openings in the stopper. The opening through the stopper was sealed around the stems with low melting point paraffin. The temperature was controlled by regulating the current passing through the resistance wire by means of a thermostat. Throughout this experiment the air stream was constant at 70.32 liters per hour, and the dewpoint of the exterior air was 4.8° C. The range of temperature was 17.8–36.1°. The range in the value of $t-t_1$ was 18.3°. The lines ot and ot_1 give the values of t and t_1 respectively. The line oy gives the calculated value of y where z [formula $y=z\ (t-t_1)$] equals 7.45 per cent. The dots show the agreement of the experimental with the calculated value of y.

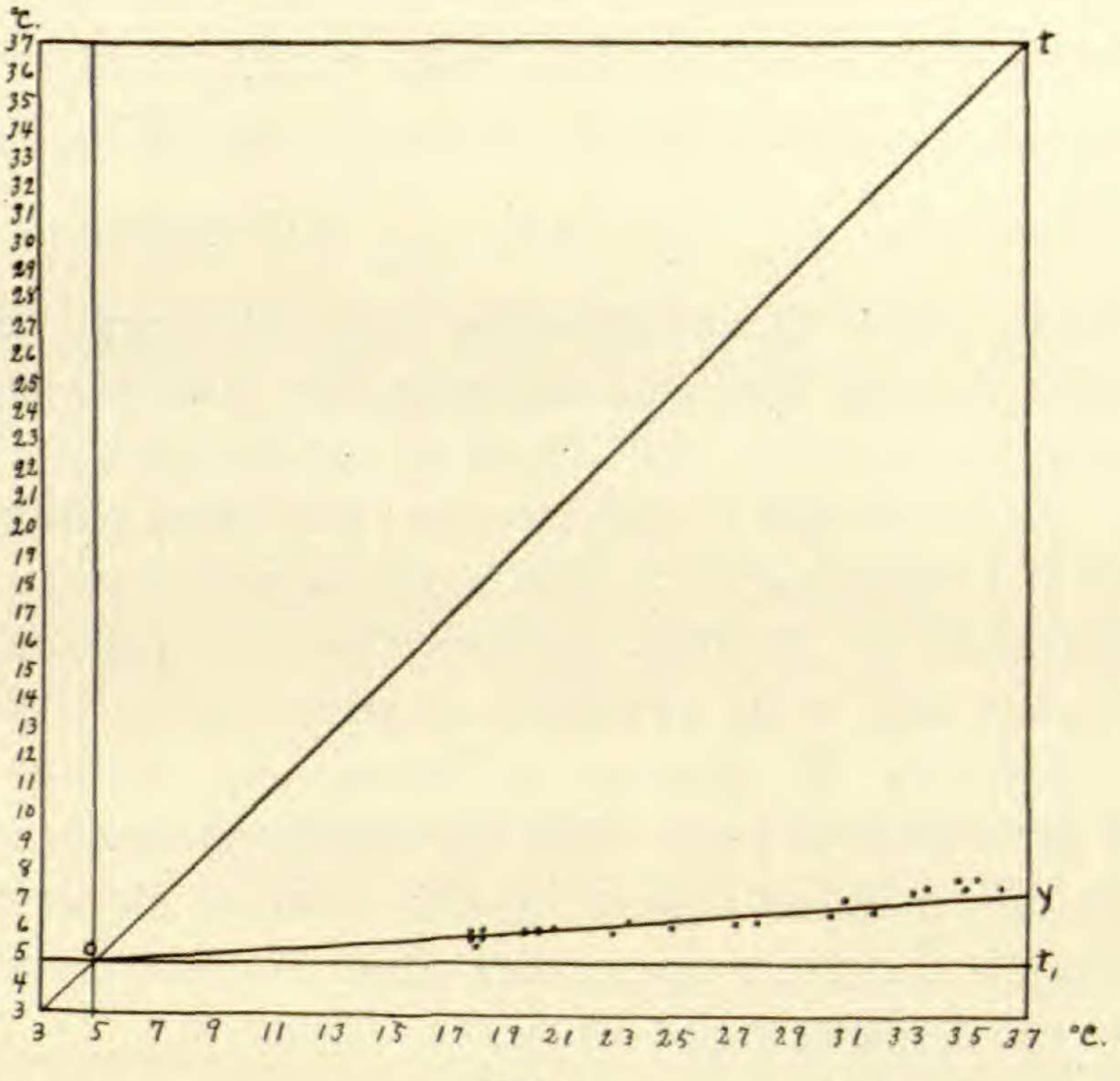

FIG. 5

This figure seems to indicate that under temperature changes of the magnitude here given, the plant acts essentially as a physical evaporating surface. On the other hand, when the relative humidity of the external air is varied, there appears to be a very decided response on the part of the plant, as is shown in the following experiment.

On March 14, 1914, a potted alfalfa plant was taken from the highly humid atmosphere of the greenhouse and brought to the much drier atmosphere of the laboratory, where the light also was not so intense as in the greenhouse. The stems of this plant were sealed into the evaporation cylinder as described (of course

TABLE IV

TIME	TEMPERATURE		LITERS AIR PER HOUR	RELATIVE HUMIDITY		DEWPOINT FOUND (x)		DEWPOINT CALCULATED INSIDE (y)	FOUND DIVIDED BY CALCULATED
	Outside	Inside		Outside	Inside	Outside	Inside		
1:44	*a* 18.0	18.3	95	25	79	−3.5	14.4	13.9	1.04
1:47	18.0	18.1	95	25	77	−3.0	13.8	13.9	0.99
1:56	18.0	17.8	95	25	76	−3.0	13.3	13.3	1.00
2:02	18.0	17.6	95	25	73	−3.0	12.4	13.5	0.92
2:19	*b* 18.1	17.2	95	?	68	?	10.8	....	....
2:36	*c* 18.2	16.0	190	?	54	?	6.1	....	....
2:53	*d* 18.2	16.6	95	?	66	?	9.9	....	....
	2:55 normal air								
3:02	*e* 18.2	16.8	95	24	71	−3.4	11.2	16.1	0.70
3:14	*f* 18.2	16.6	190	24	64	−3.4	9.4	13.5	0.70
	3:16 moist air								
3:36	*g* 18.2	18.0	95	79	91	14.3	16.4	17.3	0.95
3:44	18.2	18.2	95	81	93	14.7	17.0	17.5	0.97
3:54	*h* 18.3	18.2	190	82	94.2	15.1	17.2	17.2	1.00
3:58	*i* 18.4	18.2	95	82	96	15.1	17.5	17.3	1.01
4:04	18.4	18.3	95	82	97	15.1	17.8	17.7	1.01
	4:05 normal air								
4:09	*j* 18.4	18.1	95	28	95	−1.3	17.2	14.2	1.21
4:12	18.4	17.9	95	26	91	−2.3	16.3	13.9	1.17
4:16	18.4	17.8	95	26	85	−2.3	15.1	13.8	1.09
4:19	18.4	17.7	95	26	85	−2.2	15.0	13.7	1.10
4:24	18.5	17.6	95	26	83	−2.7	14.5	13.5	1.07
4:26	18.6	17.5	95	25	83	−2.6	14.4	13.5	1.07
4:29	18.6	17.4	95	25	81	−2.6	13.9	13.4	1.04

without removing them from their own roots growing in the pot), a current of air was drawn over them, and successive readings made, as shown in table IV.

Since the area of leaves was not changed in table IV, the simpler form of the formula $y=\frac{t-t_1}{1+c(w)^n}$ could be used; c was taken as 0.25 and n as 0.93. This high value of n is in keeping with the fact already mentioned, that when the evaporating area is large in comparison with its environment, the value of n will be large. Sixty-two leaves, having an area of approximately 200 sq. cm., were on the stems included within the cylinder. Thus it may be noted that the value of y for the slower wind movement averaged 80 per cent of the value of $t-t_1$. In this experiment both the wind movement and the humidity of the air passed over the plant were varied. The latter was accomplished by (1) using the normal air of the room, (2) first passing the air through tubes of phosphorous pentoxide and then over the plant, and (3) passing over the plant a controlled mixture of saturated and normal air. It is not assumed that the air passed over the phosphorous pentoxide was absolutely dry, but its dewpoint was so low that it could not be detected by the ether-cooled mirror, which could be easily read down to −6 or −7° C.

For the purpose of discussion the experiment may be divided into eight periods, as follows:

(*a*) 1:44–2:07, normal air, slow wind
(*b*) 2:07–2:32, dry air, slow wind
(*c*) 2:32–2:43, dry air, fast wind
(*d*) 2:43–2:53, dry air, slow wind
(*e*) 2:53–2:59, normal air, slow wind
(*f*) 2:59–3:16, normal air, fast wind
(*g*) 3:16–3:45, moist air, slow wind
(*h*) 3:45–3:55, moist air, fast wind
(*i*) 3:55–4:05, moist air, slow wind
(*j*) 4:05–4:29, normal air, slow wind

First compare the column showing the outside temperature with that exhibiting the temperature within the cylinder and measured by a thermometer having its bulb among the leaves. The temperature within the cylinder began 0.3° C. above that outside, but slowly fell throughout periods *a*, *b*, and *c*, reaching its lowest point in the later period of dry air and high wind movement when it was 2.2° below that of the outside air. When in period *d* slow wind movement was used, the cylinder temperature rose 0.6°. In period *e*, when normal air was used, the cylinder temperature rose 0.2°. In *f*, when fast wind was again used, the temperature dropped 0.2°. When high humidity air was used in periods *g*, *h*, and *i*, and the transpiration was very low, the temperature rose to within 0.1° of that of the external air, but during period *j*, when normal air was used and the evaporation increased, the cylinder temperature steadily fell, until at the end of the experiment it was 1.2° below that of the exterior air. We thus have a definitely measurable cooling effect of evaporating leaves upon the air which passes over them.

In order to study the physiological response of the plant foliage as an evaporating surface, the column giving the dewpoint inside (the dewpoint of the air after it has passed over the plant) may be compared with the next column, which shows the calculated values, considering the leaves as physical evaporating surfaces and using the constants already given. To facilitate this comparison the last column is added to give the ratio of the found to the calculated dewpoint.

It is estimated that the time required to bring the plant from the greenhouse and instal it in the transpiration apparatus and obtain the first reading was about half an hour. Suppose the evaporating condition at this time to be 104 (see last column of table). By the end of period *a*, with the plant exposed to the drier laboratory air (23 minutes), this had dropped to 92. During periods *b*, *c*, and *d* (46 minutes) the plant was exposed to air which had passed over phosphorous pentoxide. Although the comparison of the calculated with the found results cannot be made here, it may be observed that the dewpoint during period *d* was lower than during period *b*, which indicates a still further restriction of evaporation. When the plant was put back on normal air in period *e*, it was found that this restricting influence had cut down the found dewpoint to 70 per cent of the calculated value, and that this was maintained throughout the 23 minutes of periods *e* and *f*. When, however, a stream of very moist air (relative humidity 79–82 per cent) was used, the plant again responded, and within 20 minutes (reading at 3:36 P.M.) had reached an evaporation rate of 95 per cent of the calculated value. This increase continued until at 4:04 (28 minutes later) it was 101. When the shift was again made to normal air (at 4:05) there was exhibited at 4:09 (4 minutes later) a special emphasis of this high transpiring condition of the plant, since it gave a reading of 121 per cent of the calculated value. The effect of the drier normal air soon became apparent in the steady fall of this ratio, which at 4:29, or 24 minutes after removal of the moist air, had reached a value of 104, which was identical with its value at the beginning of the experiment, when it had likewise been removed from the saturated air of the greenhouse some 25 or 30 minutes previously.

The response of the plant to the humidity of the air is strongly indicated here. This response is rapid but not immediate. In looking over a number of experiments similar to the one described, it appears that when the humidity is suddenly changed but remains constant thereafter, complete adjustment is usually attained in 30–35 minutes.

It may be recalled that in the experiment involving changes in temperature only (fig. 5), the plant leaf acted approximately as a physical evaporating surface. This was true in spite of the fact that the change in the temperature of the air passing over the plant also involved a considerable change in its relative humidity. Its actual dewpoint, that is, the water contained per liter, remained constant. At the higher temperatures the actual dewpoint of the air after passing over the plant was always higher than at the lower temperatures; that is, the leaves were evaporating more into an air of higher dewpoint than at the lower temperatures. This fact approximately offsets the effect of the greater water demand made upon the plant by the greater transpiration at the higher temperature, and gives a result which is very close to the behavior of a physical surface. When, however, the water content, that is, the dewpoint of the incoming air, is increased (other conditions remaining the same), the evaporation, or the water demand upon the plant, is strongly reduced.

We may infer from this that the guard cells of the stomata become more turgid, making these openings larger, and thus increase the evaporation coefficient of the surfaces.

The use of this formula in interpreting the results of comparative tests of the transpiration of different varieties or species of plants may be illustrated by two examples. The first may be taken from seven experiments made upon a peach tree (*Prunus persica*) and a large greasewood shrub (*Covillea mexicana*), which were growing in close proximity upon well cultivated and watered soil on the grounds of the University of Arizona. The data of this experiment are given in table V, which includes the temperature within the cylinder, the dewpoint of the external air, the dewpoint of the air coming out of the cylinders, the relative humidity of the same, and the number of square centimeters of leaves used. There is then placed in the last column a calculated "standard dewpoint," which is found by means of the formula, and is the dewpoint of the outgoing air which would have been given by a physical surface of the same evaporating potentiality as the given leaves (at the time when the experiment was made), but having an area of 100 sq. cm., a cylinder (air) temperature of 30° C., and an external dewpoint of 10° C. The wind movement in all cases was the same, being approximately 85 liters per hour. It will be noted in column *e* that the dewpoint of the escaping air from the greasewood cylinder was higher three times and lower four times than the dewpoint of the air escaping from the peach cylinder. When, however, each is calculated to the standard dewpoint, that of the air from the greasewood cylinder was always higher. It is surprising to find that the leaves of the greasewood (a strictly xerophytic plant) show such a uniformly higher transpiration rate than those of the peach (a deciduous mesophyte). It is interesting to note, therefore, that, whereas 100 sq. cm. of the greasewood leaves weighed 3.93 gm., a similar surface of peach leaves weighed only 1.92 gm. When the calculations were based upon equal weights of herbage, the peach showed an equally uniform greater transpiration per 100 gm. green weight foliage. The greasewood experimented upon was growing in the orchard where it received an abundance of irrigating water. Its leaves

TABLE V

Date (a)	Plant (b)	Temperature in cylinder (c)	Dewpoint of external air (d)	Dewpoint of escaping air (e)	Relative humidity of escaping air (percentage) (f)	No. of sq. cm. of leaves used (g)	Standard dewpoint (h)	Excess of greasewood
May 21...	Greasewood.....	31	−4.3	21.9+	60	149.7	23.2	+4.3
	Peach..........	30	−4.3	18.5	53	249.4	18.9	
May 22...	Greasewood.....	33	+0.9	24.2+	61	122.2	23.7	+1.3
	Peach..........	29	+0.9	22.7	70	211.5	22.4	
May 22...	Greasewood.....	35	−2.7	23.5−	54	100.3	23.9	+1.9
	Peach..........	33	−2.7	24.3	62	206.5	22.0	
May 23...	Greasewood.....	34	−1.7	29.8−	81	178.8	26.1	+0.1
	Peach..........	34	−1.7	30.1	82	204.8	26.0	
July 1.....	Greasewood.....	38	−6.7	28.4+	60	106.5	25.5	+6.2
	Peach..........	38	−6.7	19.4	36	160.9	19.3	
July 5.....	Greasewood.....	39	+6.1	26.7−	52	94.8	22.8	+5.7
	Peach..........	42	+6.1	28.2	50	293.1	17.1	
July 12....	Greasewood.....	36	+9.5	26.9−	58	64.9	24.9	+4.6
	Peach..........	37	+9.5	27.0	59	116.1	20.3	

were very thick, green, and luxuriant, being markedly different from those growing on the dry mesa a few hundred yards distant. A single experiment comparing the orchard greasewood with that of the mesa gave a standard dewpoint 2° higher for the former. This indicates that its leaves had undergone a modification which favored a greater transpiration rate.

As an example of the use of this method in the study of the comparative water loss from different varieties of a single species, a set of eight experiments extending over a period of about two weeks may be given. These were upon two pure lines of alfalfa nos. 91 and 17. The results are collected in table VI, which has the same arrangment of material as table V. The dewpoint of the escaping air was greater for the cylinder covering branches of race no. 91 three times and less four times, but when calculated to the same standard dewpoint as used in table V, it was greater from race no. 91 for six out of the seven experiments made. These results, which would appear hopelessly confusing at first, when calculated to the standard dewpoint, seem to indicate with a fair degree of definiteness that the leaves of race no. 91 offered less hindrance to evaporation than did those of race no. 17. Here again it was the thicker leaves which gave the greater transpiration rate, since the average weight per 100 sq. cm. of race no. 91 was 2.57 gm., whereas that of race no. 17 was only 2.29 gm.

In comparing tables V and VI it will be noted that the differences in the standard dewpoints of the same species or variety for different days was often as great as or greater than the differences between the species or varieties being compared on the same day. In spite of this, however, the differences between the species or varieties were so constant that one cannot but believe they were real and significant. The differences in the standard dewpoints for different days must be sought therefore in some common factor which has influenced both types alike.

Such a factor, as shown in table IV, is the dewpoint of the external air. In examining tables V and VI it will be noted that whereas high standard dewpoints are perhaps more frequently than otherwise accompanied by high external dewpoints, this is

TABLE VI

COMPARISON OF TRANSPIRATION OF TWO PURE RACES OF ALFALFA

Date	Race no.	Temperature in cylinder	Dewpoint of external air	Dewpoint of escaping air	Relative humidity of escaping air	No. of sq. cm. of leaves	Standard dewpoint	Excess of race no. 91
May 12...	91.............	31	−0.2	19.4+	52	91.7	23.0	+1.6
	17.............	31	−0.2	16.2	43	82.8	21.4	
May 13...	91.............	27	0.0	17.2+	57	97.2	22.9	+2.1
	17.............	28	0.0	15.3	48	101.9	20.8	
May 14...	91.............	22	+3.0	15.7−	69	77.7	24.4	+0.5
	17.............	23	+3.0	15.9	66	79.6	23.9	
May 14...	91.............	25	−1.1	16.9−	66	79.4	24.5	−0.7
	17.............	24	−1.1	17.4	64	87.9	25.2	
May 15...	91.............	26	−1.0	17.4+	58	71.4	25.0	+0.2
	17.............	22	−1.0	16.0	70	99.5	24.8	
May 19...	91.............	28	−1.3	19.6−	61	83.3	25.0	+0.6
	17.............	26	−1.3	20.6	71	156.3	24.4	
May 20...	91.............	30	+2.4	23.9−	72	75.5	26.5	+0.5
	17.............	30	+2.4	24.6	75	103.4	26.0	

by no means always the case. There are other factors, for instance, such as the amount of light reaching the plant on more or less cloudy days, the age of the plants, and moisture content of the soil, all of which certainly affect the condition of the stomata and hence the evaporating efficiency of the leaves. These would, moreover, affect both types approximately alike.

Another disturbing factor, which would not equally affect the plants, is the area of foliage of each inclosed in the evaporating chamber. If such an amount of foliage is inclosed in one cylinder as to give its outgoing air a markedly higher dewpoint than that of the other cylinder, the evaporating rate per unit surface will be cut down by the greater relative humidity in the cylinder. The water demand upon a given area of the leaves will be reduced, and they will respond by opening wider their stomata. This will give the leaves of this cylinder a greater standard dewpoint than will be found for the leaves in the cylinder having the less surface exposed. In practical work, therefore, it is necessary either to inclose in each cylinder an approximately equal area of leaves (which is extremely difficult), or to so vary the wind movement as to have the dewpoint of the air, coming off each cylinder, approximately equal. This can be easily accomplished in the apparatus used by the writer, by pinching down the air supply tube of one or the other cylinders with a screw clamp.

Summary

1. As a result of evaporation experiments carried out by means of a porous cup atmometer inclosed in a glass cylinder of one liter capacity, through which an air current is passed, an evaporation formula is offered which may take any of the following forms:

$$\text{(a) } y=z(t-t_1); \text{ (b) } y=\frac{t-t_1}{1+c(w)^n}; \text{ (c) } y=\frac{t-t_1}{1+\frac{c(w)^{\frac{a}{k+a}}}{a}}.$$

In these formulae y = rise in the dewpoint of the air caused by the loss of water to it of a given evaporating surface; t = temperature of the air; t_1 = dewpoint of the outside air; z = constant used when the area and wind movement remain constant; n = exponent of w, used when the area remains constant; c = constant coefficient of w, used either when the area is constant (when a does not appear in the formula) or when a varies and hence appears in the formula; a = area of the evaporating surface which is always expressed as the ratio of the surface exposed to that exposed when c and k were determined; when c and k are determined, the area then used is taken as unity and all other areas expressed in terms of it; k = constant used in the exponent of w to adjust the area unit to the wind movement unit.

2. These formulae appear to be general in type and capable of use in any situation where y is measurable. It is possible that with some modification these formulae may also be of use when y cannot be measured, but where it is possible to measure directly the actual evaporation per unit area.

3. Under temperature changes only, alfalfa leaves appear to act as physical evaporating surfaces.

4. Changes in the dewpoint of the air result in profound changes in evaporating efficiency of leaf surfaces. This is probably a result of the opening and closing of the stomata.

5. It is possible to make use of these formulae in comparing the evaporating efficiency of different species of plants and interpreting results which would otherwise appear hopelessly confusing.

6. Distinct pure races of alfalfa exhibit measurable differences in the rate of evaporation per unit area of their leaves. Such differences may be of economic value in semi-arid or irrigated regions where production depends principally upon the efficiency of the use of the available water supply.

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